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The neutron moderators for the European Spallation Source

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Abstract.
The European Spallation Source will have 42 beam ports as a grid available for a variety of instruments, mostly neutron scattering experiments. Bi-spectral extraction for thermal and cold neutrons must be available to all the beam ports. The moderator design to deliver such neutron beams was driven by the low-dimensional moderator concept. The adopted design, consisting of one *flat* (3 cm high) moderator placed above the spallation target was considered valid for the initial instruments suite. ESS will however have a beam port system designed such that it will be possible to extract neutrons from moderators above and below the target. With all initial instruments pointing to the top moderator, this opens the possibility to have different types of moderators at the bottom, so that other neutron beams of different intensity, or spectral shape, with respect to the ones delivered by the top moderator, could be envisaged, adding additional scientific opportunities to the facility.

1. Introduction

The ESS beam extraction layout contains 42 beam ports, arranged in two sectors covering a total angle of $2\times120°$, pointing to the center of the monolith where the thermal and cold moderators are placed. The points of beam port origin at the moderators are called *focal points*.

This grid is available for placing of instruments, adding flexibility over the life time of the facility for placing of instruments. The layout for the fifteen instruments funded by the construction budget has been fixed. Additional instruments are planned to be installed in the operation phase of ESS.

The moderators to provide thermal and cold beam to the instruments were designed with the requirement to provide a bi-spectral neutron beam to all the beam ports. The thermal and cold moderators are distinct units containing different materials (light water and 20 K pure parahydrogen, respectively).

In order to provide a high thermal and cold flux, moderators should be placed above the *hot spot* of neutron production, which is an area of approximately 15×20 cm^2 where most of the evaporation neutrons are emitted from the target in the spallation process.

2. Low-dimensional butterfly moderators

2.1. Design selection

Different designs were considered for the ESS moderators since design started in 2012.

- The design presented in the Technical Design Report [1] consisted of two volume moderators, with two openings of 60 degrees each.
- The major design change was the decision to follow the low-dimensional moderator concepts [2, 3] The TDR design was replaced in 2014 by the pancake moderator [4] which consisted of a disk-shaped (3 cm height, 20 cm radius) cold moderator. The thermal neutrons were extracted from the sides. This concept was eventually abandoned in favour of the more compact butterfly moderators, with higher brightness (especially in the thermal spectrum) and easier bi-spectral extraction. Different options were considered for the bottom moderator [4], but no decision was taken at the time.
- The butterfly *BF2* design in 2015 [5] consisted of two individual hydrogen vessels, separated by a water cross. Two identical moderator sets were foreseen above and below the target, with different height: 3 cm at the top, 6 cm at the bottom. This choice was officially adopted as baseline for ESS in 2015.
- Finally the design of the top moderator was modified to the *BF1* type, presented here.

Butterfly moderators[5, 6] are the design solution to provide bright bi-spectral moderators for the whole instrument suite. Such moderators (Figs. 1,2) have the following advantages:

- Both thermal and cold moderator have a height of 3-cm for increased brightness, exploiting the advantage of flat moderators [2]. To some extent, also the concept of tube moderators [3] is exploited, thanks to the geometry of the cold moderator.
- both cold and thermal moderators are placed on the hot spot, providing high thermal and cold brightness for a required extraction area of at least 3 (height)$\times$6 (width) cm^2 for both thermal and cold moderators.
- Such moderators are ideally fit for beam extraction in the two 120° sectors; the brightness variation across the sectors is within 15%.
- Their relatively compact shape is an advantage for beam extraction: for all the 42 beam ports, the thermal and cold extraction surfaces lie next to each other, being placed on the two sides of the focal points, allowing instruments to see the brightest part of thermal and cold moderators.

3. Moderator performance

Fig. 3 shows the integrated time-averaged brightness distribution along the 42 ESS beam ports. Results are given for 3-cm and 6-cm viewed horizontal widths, as well as for the (beamline dependent) maximum horizontal widths (the vertical width is 3 cm in all cases). For the 3-cm horizontal widths, by looking at the brightest parts of the moderator extraction surfaces, it is possible to maximize thermal, and especially cold, brigthness, especially for those angles where it is possible to exploit the full depth of the cold moderator in the direction of beam extraction. Selection of the extraction surfaces should be carefully done by means of McStas simulations [7].

Fig. 4 shows the peak wavelength spectra, averaged over the 42 beam ports.

A detailed study of systematic uncertainties in the MCNPX calculations was presented in [1]. On the basis of those results, and considering the more mature level of the present design, we can expect a relative uncertainty of 15% on the present brightness values.

The performance of the ESS source is usually compared with the official ILL brightness values from the *yellow book* [8]. The original design goal of ESS was to achieve a cold peak brightness

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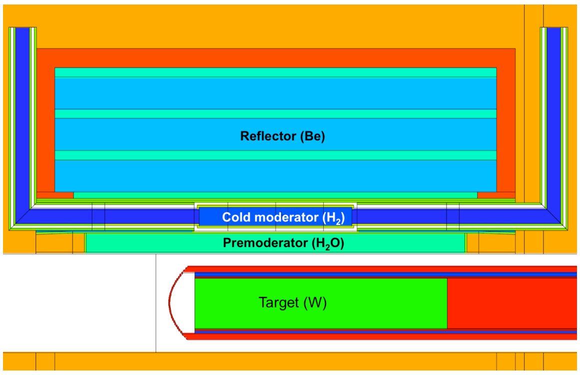

Figure 1. MCNPX [9] geometry, side view. Proton beam comes from the left impinging on the tungsten target. Tungsten (green) has a density of 15.1 g/cm^3 instead of the nominal density of 19.3 g/cm^3 to account for the fraction of helium coolant in the target according to which the filling factor of tungsten is 78 vol%. The beryllium reflector (light blue) includes water channels (green) according to engineering drawings. The reflector is contained in stainless steel (red). The outer reflector (orange) is made of stainless steel, with 10% volume fraction of water, for cooling

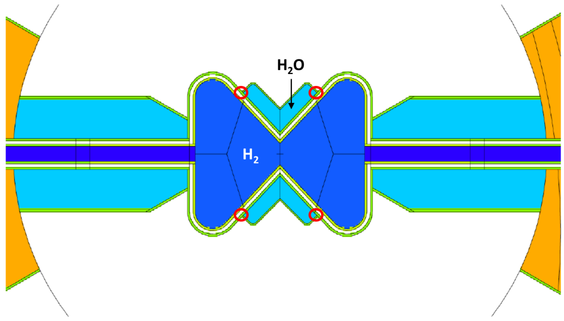

Figure 2. MCNPX geometry of the moderator, top view. The parahydrogen (blue) contains 5 vol% of Al in the model, to account for the presence of Al flow channels, not yet designed. On the sides of the cold moderator, inlet and outlet hydrogen pipes, including vacuum gaps, are modelled. Water (light blue) is placed around the pipes to serve as premoderator and increase the brightness of the cold moderator. Externally, part of the outer reflector (orange) is shown. The four focal points (origin of the beam ports) are circled in red.

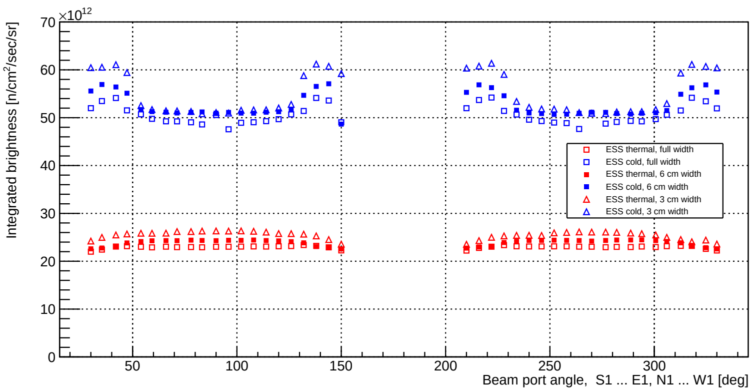

Figure 3. Time-average integrated thermal ($20 < E < 100$ meV) and cold ($E < 20$ meV) brightness for the 42 beam ports, for different horizontal projected widths: full, 6 cm and 3 cm.

30 times the average ILL brigthness [1]. With the use of low-dimensional moderators, we are far above this goal. The cold brightness shown in the present design is (at 4 Å) nearly 140 times higher than the yellow book value. The thermal brightness at 1.5 Å is about 10 times higher than ILL. Considering integral values, the integrated peak cold brightness above 4 Å for the butterfly is of 4.2 $\times 10^{14}$ n/cm^2/s/sr, which is 125 times the ILL average integrated brightness (3.3 $\times 10^{12}$ n/cm^2/s/sr). For the cold neutrons between 2 Å and 4 Å, the ESS brightness is of 9.1$\times 10^{14}$ n/cm^2/s/sr, which is 200 times the ILL brightness (4.5 $\times 10^{12}$ n/cm^2/s/sr) in the same range. For thermal neutrons, from 0.9 Å to 2 Å, the ESS peak thermal brightness is of 6.0 $\times 10^{14}$ n/cm^2/s/sr which is about 10 times higher than ILL (6.2 $\times 10^{13}$ n/cm^2/s/sr).

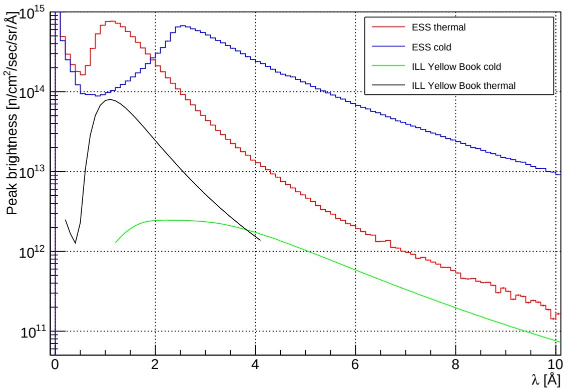

Figure 4. Brightness spectra averaged over 42 beam ports for 3 cm high moderator, compared with ILL official curves [8].

4. Future possibilities

The chosen configuration, where all initial instruments foreseen for ESS point to the top moderator, leaves open several attractive possibilities for future use at ESS. With a high-brightness moderator at the top, the bottom area could be reserved in future for a source of neutrons which should be complementary to the top one. Several possibilities could be explored, such as:

- Ultra Cold or Very Cold neutron source.
- High-intensity moderator, such as a large D_2 moderator, for specific experiments like the nnbar [10].
- A high-brightness moderator, even surpassing the brightness of the top moderator, which could be achieved either by using tube moderators (good for a few beam lines only, due to their strong directionality), or by further reducing the height with respect to the top moderator [3, 11].

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